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Amplitude modulation and demodulation of electromagnetic wave in magnetised diffusive semiconductors

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Abstract : Analytical investigations are made for the amplitude modulation as well as demodulation of an electromagnetic wave propagating in ffusive semiconductor medium. Using hydrodynamical model of semiconductor plasmas, we have found the value of modulation indices for both side l modes. Analyses are made in different wave number regions over a wide range of cyclotron frequency. It has been seen that diffusion of charge ers modifies amplitude modulation and demodulation process effectively. Numerical estimations are made for n-InSb crystal irradiated by pump e of frequency 1.6 Tera sec^{-1}. Complete absorption of the waves takes place in all the possible wave lengths regimes when the cyclotron frequency ω becomes exactly equal to carrier frequency provided one neglects the collision term in modulation/demodulation indices

Keywords : Nonlinear phenomena, acousto-optical effects, high frequency effects, plasma effects.

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1. Introduction

One of the important problems in communication systems is that of developing an effective method of modulation as well as demodulation of waves. It is a well-known fact that when an unmodulated electromagnetic wave propagates through the plasma with periodically varying parameters it gets modulated in amplitude. Max *et al* [1] already predicted that finite amplitude electromagnetic wave in a nonlinear dispersive medium can become modulationally unstable. The study of modulation can be made with respect to amplitude as well as frequency and phase. Amplitude modulation (AM) is one of the oldest forms of modulation. The efficiency of AM can either equal or exceed that of all other modulation processes such as frequency and/or phase modulations. AM is commonly encountered as a preliminary step in many complex modulation schemes.

An amplitude modulation type system transmits the carrier and both side bands simultaneously. This often makes for maximum simplicity and economy particularly at low power outputs. In communication processes, amplitude modulation is very helpful to save power by using single band transmission technique.

Photo-induced light scattering in photo refractive and Acousto-optic (AO) materials is another area of extensive research due to its potential application in optoelectronics [2-4]. Acousto-optic interaction in dielectrics and semiconductors is playing an increasing role in optical modulation and beam steering [2, 3]. However, in integrated optoelectronic device applications, the AO modulation process becomes a serious limitation due to high power requirements. The most direct approach to this problem is to tailor new material with more desirable AO properties.

The stimulus for the investigation of this type in gaseous plasma stems from the work of Volkov [5] who during the study of the stability of the plane electromagnetic wave propagating through an unmagnetised plasma anticipated self modulation of the electromagnetic waves in plasma. On the other side, the problem of amplitude modulation in semiconductor plasma has been studied by a number of workers [6-9]. The modulation of microwave while propagating through a piezoelectrically active semiconducting media duly irradiated by an acoustic wave was

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first predicted by Mathur and Sagoo [8]. The modulation of a laser beam produced due to certain plasma effects in semiconductor was reported by Sen and Kaw [9]. Lashmore-Davies [10] has described a mechanism for the spontaneous break up of shear-Alfvén wave above a certain threshold and has shown that the same mechanism could be effectively applied to study the modulational instability of other finite amplitude waves in plasmas. The earlier workers [6-9] have found a change in the modulation of an amplitude modulated electromagnetic wave. Two different mechanisms were also proposed by Sodha and Kaw [11] and Ginzberg and Gurevich [12] which were experimentally verified by Cutolo [13]. This particular change in modulation raises the possibility of demodulation of an amplitude modulated wave hence become interesting.

In most cases of investigation of nonlinear optical interactions, the non-local effects such as diffusion of the excitation density responsible for the nonlinear refractive index change has been ignored. The study of reflection and transmission of a Gaussian beam incident upon an interface that separates a linear and a nonlinear diffusive media has stimulated the idea to include diffusion in computation of nonlinear electromagnetic wave interaction in bulk and nonlinear-nonlinear interfaces [14, 15]. It is found that increased diffusion makes light transmission more difficult and tend to wash out the local equilibria of the equivalent potential representing unstable or stable TE nonlinear surface waves [16]. The high mobility of optically excited charge carriers makes diffusion effects particularly relevant in semiconductor technology as they (charge carriers) travel significant distances before recombining. Recently, the present authors [17], probably first time, reported the diffusion induced acousto-optic frequency modulation interaction in magnetised semiconductors. They have shown that the presence of enhanced diffusion due to excess charge carriers effectively amplify the frequency modulated beam in the dispersion-less acoustic wave regime.

Motivated by above discussions in this article we have presented the acousto-optic amplitude modulation of an intense electromagnetic beam in a strain dependent diffusive semiconductor crystal. The effect of diffusion of the charge carriers on the nonlinear interaction of the laser beam adds new dimensions to the analysis presented in n-type semiconductor [4]. The intense pump beam electrostrictively generates an acoustic wave within the semiconductor medium that induces an interaction between the free carriers (through electron plasma wave) and the acoustic phonons (through material vibration). This interaction induces a strong space-charge field that modulates the pump beam. Thus, the applied optical and generated acoustic waves in an acousto-optic modulator can produce amplitude modulation and demodulation effect at acoustic wave frequency. It is found that the presence of magnetic field is favourable for the phenomenon under study.

2. Theoretical formulation

This section deals with the theoretical formulation of modulation index of amplitude modulated laser beam in diffusive semiconductor. We have considered hydrodynamical model of a homogeneous semiconductor plasma of infinite extent (*i.e* $k_a l < 1$, where k_a is the wave number of acoustic mode and l the mean free path of electron). The medium considered is an n-type InSb plasma immersed in a static magnetic field ($\boldsymbol{B}_s$) pointing along z-axis which is irradiated by an intense pump (k_0) and parametrically generated acoustic wave ($\boldsymbol{k}_a$; along x-axis). The low frequency perturbations are assumed to be due to the acoustic wave (ω_a, k_a) produced by acoustic polarisation in the crystal. Due to the acousto-optical potential fields accompanying the acoustic wave, the electron concentration oscillates at the acoustic frequency. The pump wave then gives rise to a transverse current density at the frequency ω_0 and ($\omega_0 \pm \omega_a$), where ω_0 is the frequency of the pump wave. These side band current densities produce side band electric field vectors and this way the pump wave gets modulated. In the subsequent analysis, the side bands will be represented by the suffixes ±, where + stands for the mode propagating with frequency ($\omega_0 + \omega_a$) and - stands for ($\omega_0 - \omega_a$) mode.

We consider the equations of lattice dynamics in order to find the perturbed current density in crystal in presence of acousto-optic coupling which are as follows:

$$\frac{\partial^2 u}{\partial t^2} - \frac{c}{\rho} \cdot \frac{\partial^2 u}{\partial x^2} + 2\gamma \frac{\partial u}{\partial t} = \frac{\varepsilon(\eta^2 - 1)}{2\rho} \cdot \frac{\partial}{\partial x}\left(E_0 \cdot E_1^*\right), \quad (1)$$

$$\partial E_1 \qquad \frac{(\eta^2 - 1)}{\varepsilon_L} E_0 \frac{\partial^2 u}{\partial x^2} \quad (2)$$

Eq. (1) describes the lattice vibrations in an acousto-optic crystal of material density ρ; c, η and γ are respectively elastic constant , refractive index and phenomenological damping constant of the medium. The space charge field E_1 is determined from Poisson's equation (2) in which last term on RHS represents the contribution of acousto-optic polarisation

Using eqs. (1) and (2), one can obtain the perturbed carrier concentration as

$$n_1 = \left[2\rho u\left\{k_a^2 v_a^2\left(1 + A^2\right) - \omega_a^2 + 2i\gamma\,\omega_a\right\}\right] \cdot \left[e\left(\eta^2 - 1\right)E_0\right]^{-1}, \quad (3)$$

in which v_a is the shear acoustic speed in the crystal lattice given by $v_a = \left(\frac{c}{\rho}\right)$ and $A^2 = \frac{\left[\varepsilon_0(\eta^2 - 1)E_0\right]^2}{2c\varepsilon_0} = \frac{(\varepsilon_0 \beta)^2}{2c\varepsilon_0}$ is the dimensionless acousto-optic coupling coefficient due to acousto-optic interaction.

The oscillatory electron fluid velocity in presence of the pump electric field E_0 as well as that due to the fields of the sideband modes $E_\pm$, can be obtained by using the electron momentum transfer equation including diffusion effects as

$$\frac{\partial v_j}{\partial t}+(v_j.\nabla)v_j+\nu v_j=\frac{e}{m}\left[E_j+v_j\times B_s\right]=D\nu\frac{\nabla n_j}{n_j}, \quad (4)$$

where $D=\frac{k_BT}{e}\mu_e$ (Diffusion coefficient), in which the carrier mobility μ_e is given by $\left(e/_{m\nu}\right)$.

The subscript j stands for 0, + and − modes. m and ν are respectively the effective mass of the electrons and the phenomenological electron collision frequency. Using eq. (4), the velocity components can be obtained as

$$\frac{eE_j(i\omega_j+\nu)}{m\left[\omega_c^2+(i\omega_j+\nu)^2\right]}\quad 1+\frac{D\nu k^2}{\omega_c^2} \quad (5)$$

$$\frac{-eE_j\omega_c}{m\left[\omega_c^2+(i\omega_j+\nu)^2\right]}\quad 1+\frac{D\nu k^2}{\omega_c^2} \quad (6)$$

in which $\omega_c=\frac{eB_s}{m}$, is the electron cyclotron frequency and

$\frac{n_0e^2}{m\varepsilon}$ is the plasma frequency. Here, we have assumed

an $\exp[i(\omega_jt-k_jx)]$ dependence of the field quantities. The total transverse current density in the medium is given by

$$j_{total}=e\sum n_0v_j+\sum nv_0\exp\left\{i(\omega_jt-k_ax)\right\} \quad (7)$$

where $nv_0\exp\left\{i(\omega_jt-k_ax)\right\}$ represents the current generated due to interaction of the pump with acoustic wave. Using eqs. (5-7) in the wave equation given by

$$\frac{\partial^2E}{\partial x^2}-\mu\varepsilon\frac{\partial^2E}{\partial t^2}=\mu\frac{\partial j_{total}}{\partial t} \quad (8)$$

and neglecting $\exp(\mp ik_ax)$ in comparison to 1, we obtain the expressions for modulation indices as

$$\left|\frac{E_\pm}{E_0}\right|$$

$$\frac{i\omega_0\mu e^2u(i\omega_0+\nu)}{m\beta(k_a\pm 2k)}\frac{\left(2cA^2k_a^2+4i\rho\gamma\omega_a\right)}{\left[\omega_c^2+(i\omega_0+\nu)^2\right]}\left[1+\nu Dk^2/\omega_c^2\right]. \quad (9)$$

By equating the real parts of above equation, through rationalisation, we find

$$\frac{E_\pm}{E_0}=\frac{-2\omega_0\mu e^2k_au}{m\beta(k_a\pm 2k)}$$

$$\frac{cA^2\omega_0\left(\omega_c^2-\omega_0^2-\nu^2\right)+\frac{2\rho\gamma\nu_a\nu}{k}\left(\omega_c^2+\omega_0^2+\nu^2\right)}{\left[\left(\omega_c^2-\omega_0^2+\nu^2\right)^2+4\nu^2\omega_0^2\right]}$$

$$1+\frac{\nu Dk^2}{\omega_c^2} \quad (10)$$

It may be seen from above expression that the carrier diffusion effectively modify the value of modulation indices in semiconductor plasma.

3. Results and discussion

In this section, we analyse eq. (10) to discuss the amplitude modulation and demodulation due to acousto-optic interaction in the presence and absence of carrier diffusion. One can see that diffusion process modifies the results effectively. Eq. (10) for the modulation index in semiconductor materials can be analysed and discussed in two different wave number regimes *viz.* (i) $k_a>2k$, and (ii) $k_a<2k$.

(i) When $k_a>2k$:

In this wave number regime, the amplitude of the side band modes ($E_\pm$) always remain out of phase with pump wave in the permissible cyclotron frequency range. However, when the carrier frequency becomes equal to the cyclotron frequency, complete absorption of waves takes place provided one neglects the collision term in eq. (10). These out of phase side-bands then interact with the pump wave under this condition to produce demodulated acoustic wave. Hence in $k_a>2k$ regime, one can always get demodulation. The demodulation index is found to be maximum at a particular value of magnetic field when $\omega_c=\omega_0$.

As a typical case, numerical estimations have been made for n-InSb at 77K using the physical constants: $m=0.014\,m_0$, $\varepsilon_L=17.8$, $\nu=4\times10^{11}\,sec^{-1}$, $\omega_0=1.6\times10^{13}\,sec^{-1}$, $\rho=5.8\times10^3$ kg m^{-3}, $\gamma=2\times10^{10}$ sec^{-1}; m_0 being the free electron mass. The crystal is assumed to be irradiated with an acoustic intensity $=10^4$ W m^{-2} at frequency $\omega_a=10^{12}$ sec^{-1}. The variations of $\left(\frac{E_+}{E_0}\right)$ and $\left(\frac{E_-}{E_0}\right)$ with the applied magnetostatic field (ω_c) are depicted in Figures 1 and 2 in absence and in presence of carrier diffusion respectively. In the considered case, diffusion coefficient D (= KT/mv) has been taken equal to 0.23829 m^2 sec^{-1} on the basis of physical constants chosen above. It may be inferred from Figures 1 and 2 that the demodulation indices of both the side bands increase with cyclotron frequency $(\omega_c < \omega_0)$. These indices become maximum at $\omega_c \approx \omega_0$. A slight tuning $(\omega_c > \omega_0)$ at this resonance point, decrease both the indices abruptly to zero. It may be inferred from these figures that diffusion effectively altered the index parameter by increasing their values for both the modes at $\omega_c \approx \omega_0$.

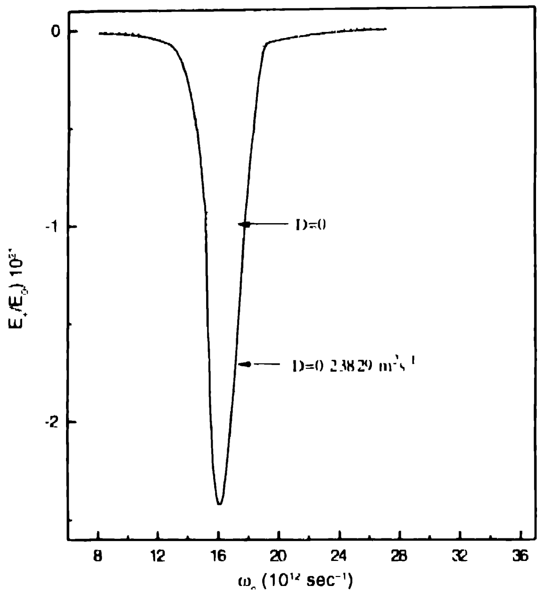

Figure 1. Variation of modulation index of plus mode (when $k_u > 2k$) with magnetic field ($D = 0$.) and $D = 0.23829$ m² sec⁻¹ —)

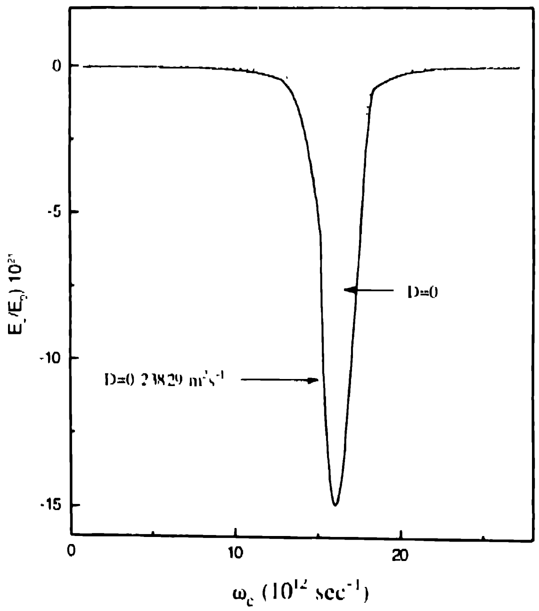

Figure 2. Variation of modulation index of minus mode (when $k_u > 2k$) with magnetic field (ω_c) ($D = 0$: .) and $D = 0.23829$ m² sec⁻¹ .—)

(ii) When $k_u < 2k$.

Under this condition, the behaviour of modulation index for plus and minus modes are opposite in nature. Variation of E_+ with applied magnetic field (ω_c) is shown in Figure 3. It may be inferred from this figure that the amplitude of plus mode

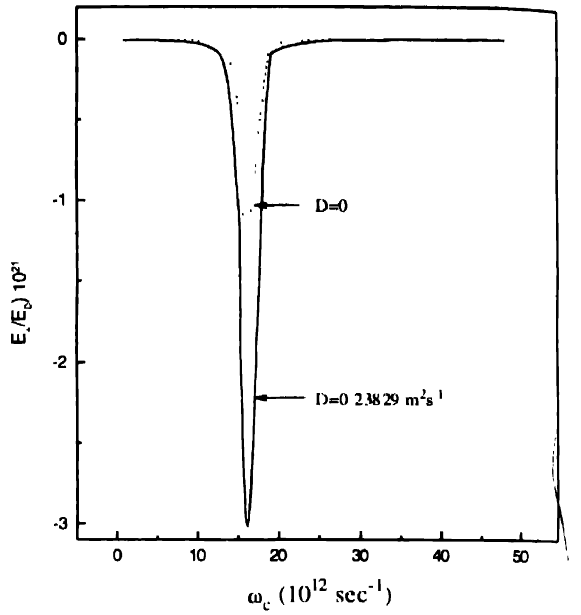

Figure 3. Variation of modulation index of plus mode (when $k_u < 2k$) with magnetic field (ω_c)

is out of phase with pump which shows demodulation process and again at $\omega_c = \omega_0 = 1.6 \times 10^{13}$ sec⁻¹, we find that the demodulation is maximum. Figure 4 depicts the variation of $\left(\frac{E_-}{E_0}\right)$ with magnetic field (ω_c), which depicts that amplitude of minus mode and pump amplitude are in phase; hence modulation occurs. Here the modulation of minus mode may be attributed to the sign of factor $(k_u - 2k)$ under $k_u < 2k$ regime

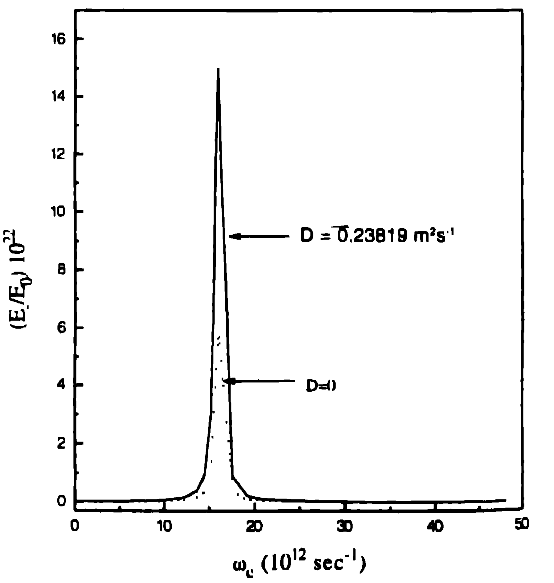

Figure 4. Variation of modulation index of minus mode (when $k_u < 2k$) with magnetic field (ω_c).

The above discussion reveals that the amplitude modulation nd demodulation of an electromagnetic wave by an acoustic vave can easily be achieved in acousto-optic crystal. The carrier iffusion coefficient always increases the value of modulation/ emodulation indices for both the modes around $\omega_c \approx \omega_0$. It nay be inferred that the diffusion altered the result favourably. Hence, the consideration of a diffusive crystal with acousto-optic polarisation thus possibly offers an interesting area for ne purpose of investigations of different modulational nteractions and one hopes to open a potential experimental ool for energy transmission and solid state diagnostics in cousto-optic diffusive crystal.

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